Collapse challenge for interpretations of quantum mechanics

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Abstract. The collapse challenge for interpretations of quantum mechanics is to build from first principles and your preferred interpretation a complete, observer-free quantum model of the described experiment (involving a photon and two screens), together with a formal analysis that completely explains the experimental result. The challenge is explained in detail, and discussed in the light of the Copenhagen interpretation and the decoherence setting.

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1 The challenge

In spite of 80 years of work (see, e.g., the reprrint collection by Wheeler & Zurek [7]), the foundations of quantum mechanics are still full of riddles, partly due to the vagueness of the goal to be explained. This paper proposes a simple test that the ultimate interpretation would have to meet.

A single photon is prepared in a superposition of two beams. A photosensitive screen blocks one of the two beams but has a big hole where the other beam can pass without significant interference. At twice the distance of the first screen, a second photosensitive screen without hole is placed.

The experimental observation is that the photon is observed at exactly one of the two screens, at the position where the corresponding beam ends (and **not** in a superposition or mixture of these two possibilities).

The challenge is to build from first principles and your preferred interpretation a complete, observer-free quantum model of this experiment (one photon, two screens, and an appropriate environment), together with a formal analysis that completely explains the experimental result.

Remark. This challenge was first posed (in essentially unaltered form) on June 28, 2004 in the newsgroup sci.physics.research. The following discussion makes the challenge more precise and evaluatues how the two most frequently invoked interpretations of the measurement process fare in the challenge. Useful additions to this discussion will be made available on the WWW [3].

2 Comments

1. The experimental result has the natural interpretation that the photon was either stopped by the first screen, or passed that screen successfully. This property is essential for the analysis of any quantum experiment which uses screens with holes (or similar filters) to create or select beams of particles. Thus reproducing this experiment correctly is a basic requirement for any interpretation claiming to provide complete foundations for quantum mechanics.

2. Note that it is possible (though not easy) to prepare states with definite photon number to reasonable accuracy; see Varcoe et al. [6]. Combining

this with a half-silvered mirror is a way to achieve the preparation required in the challenge.

3. Unitary dynamics demands that the system (photon,screen1,screen2), characterized – after tracing out all other degrees of freedom – by basis states of the form

$$|\text{photon number, first screen count, second screen count}\rangle,$$

evolves from a pure initial state $|1,0,0\rangle$ into a superposition of $|0,1,0\rangle$ and $|0,0,1\rangle$, while agreement with experiment demands that the final state is either $|0,1,0\rangle$ or $|0,0,1\rangle$. This disagreement is the measurement problem in its most basic form.

4. Clearly, the experimental result is something completely objective, about which all competent observers agree. (This is my definition of objectivity.) Thus the analysis is not permitted to have any dependence on hypothetical observers.

5. Memory, records, etc. are permitted only if they are modelled as quantum objects, too, and the properties assumed about them (such as permanence or copyability) are derived from first principles, too.

6. Position, momentum, and time are required to be modelled explicitly; apart from that, appropriate simplifications are permitted. For example, it is ok to treat the photon as a scalar particle, to restrict to a single space dimension, or to choose a tractable interaction.

7. Approximations are allowed to make the mathematics more tractable; but approximations that require for their justification a collapse argument are forbidden

8. One can calculate observation probabilities by calculating interactions of the photon with a single electron in the screen (which is emitted and later magnified if the photon is observed), which is fine (and explains everything if the collapse is assumed). But this does not help to solve the collapse problem itself. Calculating S-matrix elements only means that one then knows the superposition into which a state develops; but the challenge is about how this superposition of the possible outcomes with their associated probabilities collapses into one of the observed states. Why does one not end up in a superposition of the state where an electron is emitted (and observed by macroscopic magnification) from the first screen only, and the state where an electron is emitted (and observed by macroscopic magnification) from the second screen only? Such macroscopic superpositions are not observed.

9. A subjective probabilistic answer is not satisfactory since we have only a single photon. What makes different physical observers agree that the first screen and not the second detected the photon? Clearly, this question is within the realm of physics and should be answerable by a fundamental theory underlying all of physics.

3 Analysis of the Copenhagen interpretation

The Copenhagen interpretation (see, e.g., von Neumann [4]) – which renounces unitarity at measurements – is unsurpassed in its simplicity, and almost meets the challenge.

Indeed, in the Copenhagen interpretation, the state remains $|1, 0, 0\rangle$ until the photon feels the presence of the first screen. In the next split moment, the state collapses, due to interaction with the classical screen, to either $|0, 1, 0\rangle$ or $|1, 0, 0\rangle$. In the first case, the photon is destroyed and we reached a stationary state. In the second case, the state remains $|1, 0, 0\rangle$ until the photon feels the presence of the second screen. In the next split moment, the state turns into $|0, 0, 1\rangle$, due to interaction with the second screen.

The only thing missing is the required quantum model of the screens. Although very successful in all situations where the experimental setting can be interpreted classically, this unresolved quantum-classical interface issue (including the missing definition of which situations constitute a measurement) is a serious defect of the Copenhagen interpretation when viewed as a fundamental interpretation of quantum mechanics.

4 Analysis of decoherence interpretations

Decoherence scenarios (see, e.g., Joos et al. [2]) go something like the following.

Localized position states (of the emitted electron; the photon is absorbed hence no longer exists) are robustly selected by screen plus environment. This can be justified roughly by noting that the interaction between the photon and the emitted electron is given by some local operator. (While some handwaving is involved in this argument since there are many electrons

but only one is emitted; this can probably be cured by an appeal to quantum field theory.)

Assuming this robustness and some handwaving that can be made more precise, decoherence shows that the reduced state of (photon + two screens) is not a superposition but a mixture of the two states $\phi = |0,0,1\rangle$ and $\chi = |0,0,1\rangle$ in question. The reduced state is $\rho = (\phi\phi^* + \chi\chi^*)/2$, if initially both beams had the same intensity.

But this mixture cannot be interpreted as an ensemble of pure states in one of the two robust configuraions since it is the partial trace of a pure state, and hence something irreducible. It is not allowed to treat $\rho = \mathrm{tr}_E \psi\psi^*$ (where ψ is the state of photon+screens+environment, and the trace is over the environment E) as an ensemble consisting of 50% copies of $\phi\phi^*$ and 50% copies of $\chi\chi^*$ – not even for a large stream of photons – since there is no way to decompose $\psi\psi^*$ into two states whose partial traces are $\phi\phi^*$ and $\chi\chi^*$. But in fact we only have a single photon, and there it is completely ridiculous. What one actually observes is one of $\phi\phi^*$ and $\chi\chi^*$, and not the mixture.

Erich Joos, one of the exponents of decoherence theory and coauthor of the book [2] on decoherence, explicitly states this missing step in the last paragraph of p.3 in [1]. The same conclusion is reached in the excellent article by SCHLOSSHAUER [5].

Thus decoherence only fakes the real situation, and does not explain the collapse.

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